MEMS SENSOR FOR DETECTING STRESS CORROSION CRACKING

RELATED PATENT APPLICATION

This application claims the benefit of U.S. Provisional Application Serial No. 60/450,862 filed February 28, 2003 and entitled "MEMS Sensor for Detecting Stress Corrosion Cracking".

TECHNICAL FIELD OF THE INVENTION

This invention relates to sensors for detecting the effects of stress and corrosion on materials, and more particularly to such a sensor made using MEMS technology.

BACKGROUND OF THE INVENTION

Many engineering structures are subjected to the simultaneous conditions of an applied stress (or load) and a corrosive environment. This combination of stress and corrosion can lead to material failures that might not occur from either condition alone, or that would take longer to occur from either condition alone. The resulting material failure is known as "stress corrosion cracking", and can cause structural failure of equipment such as boilers, pressure vessels, oil and gas piping, bridges, vehicles, and aircraft.

There are a number of existing methods for measuring susceptibility to stress corrosion cracking, and for measuring crack propagation rates. One limitation of existing methods is that their detection of crack propagation rates is limited. A typical limit of 10^{-11} meters per second is too high to determine whether stress corrosion cracking will lead to failure of highly resistive materials over a long time period. Another limitation of existing methods is that they are not easily implemented as sensors for real-time real-world monitoring.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a plan view of a sensor in accordance with the invention, and having a "single arm" beam.

FIGURE 2 is a plan view of a sensor in accordance with the invention, and having a "double arm" beam.

FIGURE 3 illustrates a sensor with a single-arm beam and an on-chip actuator.

FIGURE 4 illustrates a sensor with a double-arm beam and an on-chip actuator.

FIGURE 5 illustrates a sensor with two on-chip actuators and configured for capacitive measurement.

DETAILED DESCRIPTION OF THE INVENTION

The following description is directed to sensors and methods for monitoring materials for stress corrosion cracking. The propagation of such cracking is detected and measured using MEMS (micro-electromechanical systems) sensors. The sensors are small and have broad application. They measure cracking that results from the combined effects of both stress and corrosion.

The various embodiments of the sensor all include a sample of the material of interest, in the form of a tiny cantilevered beam. This beam is designed to crack in response to the combination of stress applied to the beam and from being placed in a corrosive environment. The sensor further includes electrical connections for measuring the extent of any cracking in the beam, and may also include actuators used for applying stress to the beam. The beam, the electrical connections, and actuators are integrated on the substrate.

The sensors may be used in-situ, such as by placement in the same real world environment in which the material of interest is to be used. In this manner, the sensor's beam undergoes the corrosive effects of the environment of interest. The sensors may also be used "predictively" by being placed in an artificial environment that is similar to the conditions under which the material of interest would be used. In either case, the beam is subjected to environmental conditions that may cause it to undergo cracking.

Regardless of whether the environmental conditions are real-world or artificially induced, the beam is also mechanically stressed. The stress may be applied using

on-chip actuators, or the sensor may be fabricated without actuators and the stress applied manually. The stress may also be the result of the fabrication process, i.e., residual stress.

The stress can be applied prior to, during, or after, the placement of a sensor in the environment of interest. When the beam is stressed prior to being subjected to environmental conditions, it is referred to as being "pre-stressed".

FIGUREs 1 - 5 illustrate various embodiments of MEMS sensors in accordance with the invention. FIGURE 1, and the other figures of this description, are plan views of a single sensor device ("chip"). It is assumed that each of these sensors includes, and is fabricated on, a substrate, such as substrate 18 of FIGURE 1, using fabrication techniques known in the art of MEMS fabrication.

Referring to FIGURE 1, sensor 10 is referred to herein as a "single arm" embodiment, and has a cantilevered beam 11. As stated above, beam 11 is fabricated from a material that is the same as the material of interest. For example, if the material of interest is used in an airplane structural member, such as a high strength aluminum alloy, beam 11 could be fabricated from aluminum. Alternatively, beam 11 may be fabricated from an analogous material, that is, a material that responds to stress and corrosion in the same manner as the material of interest. In the various embodiments of this description, it is assumed that the beam is electrically conductive, so that voltage can be

applied to the beam for the purpose of resistive or capacitive measurements.

The fixed end of beam 11 is attached to pad 13. The free end of beam 11 is moveable across the surface of the substrate, as indicated by the arrow. Beam 11 is pre-notched at point A to encourage any cracking to occur at point A. To further encourage cracking only at point A, beam 11 is widened near its point of attachment to pad 13. In FIGURE 1, beam 11 is notched at its right side, which implies that stress will be applied so as to move beam to the left, as indicated by the arrow.

The free end of beam 11 is narrowed to form a needle end 11a. As beam 11 moves to the left, needle 11a passes over a displacement scale 15. Scale 15 permits the displacement of beam 11 to be visually inspected, and thus the amount of stress placed on beam 11 to be measured.

Electrical contact pads 12 and 13 permit electrical connections to be made to beam 11, via electrical leads 14. Pad 13 is fixed, but pads 12 are moveable along the surface of sensor 10, in response to movement of beam 11. In other words, pads 12 "float" on the surface of the substrate 18, and are not fixed to the substrate. Guides 12a may be fabricated in a manner that constrains the movement of pads 12 to a plane slightly above the substrate and prevents vertical movement. In other embodiments, pads 12 may be tethered or otherwise attached to substrate 18, but in a manner that permits their electrical leads to follow movement of beam 11, if any.

In the embodiment of FIGURE 1, sensor 10 does not include any actuators. Beam 11 is stressed manually, and as stated above, the application of stress and the exposure to environmental conditions need not occur simultaneously.

In operation, for measuring cracking as indicated by resistivity changes in beam 11, pad 13 connects beam 11 to ground. Pads 12 are used to measure a drop in applied voltage from one pad 12 to the other. When subjected to applied stress and to the corrosive effects of the environment, beam 11 will crack at point A. The air gap resulting from the crack increases the resistance of beam 11 from a point on one side of the crack to a point on the other side of the crack. Thus, if a pad 12 is placed on either side of the crack, changing voltage differences between them can be used to measure changes in resistance within beam 11. Thus, as the crack propagates, the cross sectional area of the metal available to carry current decreases and the measured resistance of the beam continues to increase proportionally.

FIGURE 2 illustrates a sensor 20 having a "double arm" beam 21. The right arm of beam 21 is intended to be pulled to the right, as indicated by the arrow in FIGURE 2. The area of interest of beam 21 is at point B where the two arms meet. This is the area most likely to exhibit cracking as the result of the combined effects of the stress and corrosion.

Like sensor 10, sensor 20 is configured to measure changes in resistivity resulting from a decrease in cross sectional area of beam 21 associated with a propagating crack. FIGURE 2 operates in a manner similar to

FIGURE 1, except that voltage is applied across two pairs of pads. Pad 23 is connected to ground. Pads 22 are moveable, but pads 26 need not be. Pads 22 have electrical leads 27 to the left arm of beam 21, and pads 26 have electrical leads 24 to the right arm of beam 21.

In operation, typically, the voltage is applied across pads 26 and across pads 22. The resistivity measurements measure resistance within either arm of beam 21 at different distances from the point of failure (the crack at point B).

FIGURE 3 illustrates a sensor 30, which has a single-arm beam 31, which is similar to that of sensor 10. However, sensor 30 includes an on-chip MEMS actuator 39. In the example of this description, actuator 39 is a scratch drive actuator, but many other types of actuators could be used.

In operation, actuator 39 is activated to apply force to beam 31, so as to push beam 31 in the horizontal direction, as indicated by the arrow in FIGURE 3. Other actuators might operate differently so as to move beam 31 in either horizontal direction or in one or more vertical directions. The force may be applied and held, applied for a selected duration, or may be applied periodically.

Electrical leads 38 provide an electrical connection from beam 31 to electrical pads 32. In the example of FIGURE 3, leads 38 are made from a metal such as gold, and are thinner than the leads of FIGUREs 1 and 2, which are made from metal and polysilicon.

As in the embodiment of FIGURE 1, pad 33 is fixed and pads 32 are moveable across the substrate. Pad 33 is connected to ground and a voltage is applied across pads

32. Changes in resistivity indicate the extent of cracking.

Changes in the load applied by actuator 39 necessary to maintain a specific displacement of beam 31 can be measured. This may be accomplished by determining the voltage or current consumed by the actuator 39, or by inspecting scale 34.

FIGURE 4 illustrates a sensor 40 having a double-arm beam, similar to that of sensor 20. However, sensor 40 includes an on-chip actuator 49. Actuator 49 is attached to the right arm of beam 41, and operates so as to pull that arm of beam 41 to the right. Pads 42, 43, and 46 are similar in structure and operation to the corresponding pads of FIGURE 2.

FIGURE 5 illustrates an alternative method for measuring crack propagation. As in the other embodiments, beam 51 cantilevered and has a fixed end attached to pad 52. Although the portion of beam 51 near the fixed end is made from the material of interest, the portion of beam 51 near the free end may be made from a different material. This portion of beam 51 need not be made from the material of interest as its function is to provide greater registration of movement of the free end of beam 51 in response to applied stress.

An actuator 54 is placed on either side of the free end of beam 51. Each actuator 54 is operable to apply force in a horizontal direction that opposes the other. As beam 51 moves, the narrowed end ("needle") of beam 51 passes over a capacitance meter 55. The end of beam 51 acts as one plate of a capacitor, and meter 55 has a series of "fins" that act as the second plate of the

capacitor. As the needle end of beam 51 moves across meter 55, the capacitance is measured. Electrical connections run from each meter 55 to electrical pads 56. The applied voltage at the fixed end of beam 51 or via the pads 56 are appropriate for measuring capacitance between the free end of beam 51 and the meter 55.

In alternative embodiments, a capacitance measurement system may be used with a feedback loop to actuators 54 to maintain a fixed position of needle 51a. The capacitive measurement configuration of FIGURE 5 could also be implemented with only a single actuator.

The various embodiments described above are each implementations of a method of using MEMS sensors that incorporate a material of interest that is monitored for stress corrosion cracking. The resulting cracking is measured electrically. In this manner, the effects of both stress and the environment can be monitored.

When the device is stressed and placed in situ, the effects of stress on the beam mimic those of an actual structural element. The corrosion on the beam is the same as on the actual element. In this manner, the effects of both stress and the environment on an actual structural element are monitored. The sensor stress can be applied and measurements can be made "on line", in the sense that electrical connections can be maintained while the sensor is placed in the environment of interest.